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ORIGINAL RESEARCH

The Role of Urban Trees in $PM_{2.5}$ Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys

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ABSTRACT: Rapid urbanization is intensifying air pollution across cities worldwide, with fine particulate matter ($PM_{2.5}$) emerging as one of the most hazardous pollutants to public health. While urban trees are widely recognized for their role in air purification, particularly through pollutant absorption and filtration, most existing studies rely on predictive models such as i-Tree Eco and rarely incorporate direct field-based validation of $PM_{2.5}$ exposure levels for urban residents. A critical gap remains in understanding the actual distribution of health-threatening $PM_{2.5}$ concentrations and the localized effectiveness of urban vegetation in mitigating these pollutants. This study addresses this gap by assessing $PM_{2.5}$ pollution levels and evaluating the particulate matter absorption capacity of urban trees in two street alleys with contrasting tree canopy cover (TCC) in Warsaw, Poland. The research was conducted in two phases: first, $PM_{2.5}$ concentrations were monitored using dust sensors during peak and post-peak traffic periods; second, the i-Tree Eco model was employed to quantify pollutant uptake by trees at each site. The findings indicate that exceedances of the WHO $PM_{2.5}$ air quality standard (15 µg/m^3) occurred 1.5 times more frequently on streets with only 6% tree canopy cover (TCC), compared to streets with more than 30% TCC. Moreover, the site with optimal TCC, trees demonstrated over 14-fold greater effectiveness in $PM_{2.5}$ removal. Furthermore, the model has been shown to be statistically significant, meaning that one of the predictors, TCC or DBH, has a significant impact on $PM_{2.5}$ removal levels. These findings highlight the critical role of tree canopy density in enhancing urban air quality and suggest that sole reliance on modeled estimations without ground-level data may significantly underestimate residents' exposure to $PM_{2.5}$. By integrating in-situ pollution monitoring with ecosystem service modeling, this study provides a more accurate assessment of urban trees' capacity to mitigate air pollution. The findings underscore the need for data-driven urban greening policies and offer actionable insights for improving air quality in cities like Warsaw.

KEYWORDS: Air pollution, $PM_{2.5}$ mitigation, tree canopy cover, urban forestry, vegetation absorption

1. Introduction

Air pollution has become one of the most serious environmental and public health challenges of the 21st century, particularly in densely populated urban areas. The rise in global urbanization, industrial activities, traffic congestion, and diminishing green spaces has led to the widespread degradation of air quality. According to the World Health Organization, more than 90% of the world's population resides in areas where air quality exceeds recommended limits, with urban populations being most vulnerable to its effects (Akbari et al., 2001).

Particulate matter (PM), especially PM_{10} and $PM_{2.5}$, is considered among the most harmful air pollutants due to its small size and ability to penetrate deep into the human respiratory system. These particles primarily originate from vehicle emissions, industrial activities, open burning, and fossil fuel combustion (Aslam et al., 2021). Much of the research has focused on the impact of air pollution on health problems, where it has been shown that once inhaled, fine particles can reach the alveoli in the lungs and enter the bloodstream, contributing to a wide range of health problems including asthma, bronchitis, cardiovascular diseases, chronic obstructive pulmonary disease (COPD), and lung cancer (Bass, 2001; Bates, 2005). Studies have shown that even short-term exposure to elevated $PM_{2.5}$ levels can increase hospital admissions and premature mortality, especially among vulnerable groups such as children and the elderly (Beckett et al., 1998). For instance, research conducted in Beijing reported that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ levels was associated with a statistically significant rise in lung cancer incidence among both men and women (Beckett et al., 2000).

In addition to its health effects, air pollution contributes to environmental degradation and economic loss. It leads to reduced agricultural productivity, damages buildings and cultural monuments, and increases healthcare costs (Bond, 2013). Despite global efforts to regulate emissions and promote cleaner technologies, urban air pollution continues to rise, especially in developing and transitional economies where enforcement of environmental regulations remains weak.

One promising strategy to combat air pollution involves the use of urban vegetation, particularly trees, which offer a cost-effective and sustainable means of improving air quality. Trees and other green infrastructure components provide a range of ecosystem services, including shading, temperature regulation, carbon sequestration, and—most importantly—pollution removal from the atmosphere (Bonire and Gbenga-Ilori, 2021; Branea et al., 2016). Through the processes of dry deposition and stomatal uptake, trees can trap and absorb particulate matter on leaf surfaces or within plant tissues, effectively reducing airborne concentrations of harmful pollutants (Brantley et al., 2014). Research from cities like Christchurch (New Zealand), London (UK), and New York (USA) has demonstrated that urban trees can remove hundreds of tons of air pollutants annually, thereby contributing significantly to public health and environmental quality (Brauer et al., 2007; Bureau. 2007).

However, the effectiveness of different tree species and vitality in removing PM varies considerably. Factors such as leaf surface micromorphology, canopy density, stomatal behavior, waxy cuticle thickness, and tree architecture influence the capacity of trees to capture or absorb airborne particles (Burkhardt, 2010; CAFE 2004; Song et al., 2025; Popek et al., 2024; Hoppa et al., 2025; Przybysz et al., 2024). Coniferous trees and rough-leaved deciduous species, for example, tend to accumulate more PM than smooth-leaved species due to their surface characteristics (Cavanagh, 2008). These differences highlight the need for localized, species-specific assessments to inform urban forestry practices aimed at pollution control.

To estimate the pollution mitigation potential of trees, several analytical models and tools have been developed. One of the most widely adopted is the i-Tree Eco model, created by the U.S. Forest Service. This model calculates a range of ecosystem services provided by urban forests, including air pollution removal, carbon storage, and avoided stormwater runoff, based on tree species, structure, and local meteorological data (Cavanagh et al., 2009). The i-Tree model has been successfully applied in multiple urban contexts—including New York City, Dublin, Krakow, and London—to quantify the environmental contributions of trees (Cen, 2015; Chenet al., 2017). Additionally, other studies have utilized GIS-based spatial modeling, leaf-level PM deposition assessments, or atmospheric dispersion models to evaluate vegetation-air quality interactions (Chen et al., 2017).
Moreover, in Central and Eastern Europe—particularly in Warsaw, Poland—applications of the i-Tree model remain limited, and empirical evidence on the particulate matter absorption efficiency of local tree species is lacking. Thus, there is a need for localized assessments that integrate urban forestry with air quality management to better guide policy and planning.

Despite growing global interest in nature-based solutions for pollution control, empirical data on species-specific pollution mitigation potential in Warsaw's urban environment are scarce. Moreover, recent trends in urban development in Poland, including the replacement of green spaces with impervious infrastructure, threaten to reduce the natural capacity of cities to cope with pollution (Chen, 2006). Understanding the role of existing urban trees in PM reduction, and identifying urban forest characteristic with the highest mitigation potential, is crucial for promoting environmentally sustainable urban planning (Konijnendijk, 2023; Lopez et al., 2025; Iqbal et al., 2025). For example, the mentioned above and widely discussed 3-30-300 guideline aims to establish a standard for enhancing urban dwellers' well-being, strongly linked to ecosystem services, including urban flooding mitigation (Vesuviano et al., 2025), improvements in mental and physical health, and reduction of overweight prevalence (Helbich et al., 2025); Zheng et al., 2024], as well as lower mortality rates among city residents (Giannico et al., 2025). This study aims to assess the capacity of roadside urban trees in Warsaw to mitigate particulate matter (PM_{10} and $PM_{2.5}$) pollution using the i-Tree Eco model. The research questions are: (1) Does tree canopy cover (TCC) influence pollution levels in relation to street trees? (2) Does optimal TCC significantly reduce the likelihood of substantial exceedances of air quality standards that pose a threat to human health?

These questions are addressed through an analysis of measured pollution levels and simulations of $PM_{2.5}$ removal efficiency using the i-Tree Eco model, in the context of a minimum 30% TCC, which recent studies identify as optimal (Konijnendijk, 2023). Based on the existing literature, we hypothesize that local urban forest characteristics influence the efficiency of particulate matter (PM) removal: 1) the pollution removal efficiency of urban forests significantly varies with TCC (e.g., Marszałkowska Street <30% and Żwirki i Wigury Street >30%); 2) locations with differing TCC values will differ in the prevalence of high pollution levels, categorized as below 15 µg/m³ and above 15 µg/m³; and 3) removal efficiency is associated with tree diameter at breast height (DBH). By addressing these objectives, the study seeks to contribute to evidence-based policymaking and support Warsaw's efforts toward building greener, healthier, and more resilient urban ecosystems.

2. Materials and methods

2.1 Description of the study site

Warsaw, the capital of Poland and the largest city in the country, situated at the heart of Europe, was chosen as the research area (Figure 1). With a surface area of 517.2 km² and a population of 1,792,718 (Poland in numbers, 2020), Warsaw, like many other Polish cities, grapples with severe air quality issues on a global scale. In January 2017, the city experienced one of its most severe smog episodes, with pollution levels exceeding air quality standards across much of Poland.

Figure 1. Tree inventory along Marszałkowska and Żwirki i Wigury streets in Warsaw, Mazowieckie, Poland, showing tree ID numbers and locations on aerial imagery.

During this period, the permissible average concentrations of PM_{10} were surpassed on 19-22 days, accounting for 60-70% of the month, while $PM_{2.5}$ concentrations exceeded standards on 25-28 days, covering 80-90% of the month (Karaczun & Michalak, 2019). In January 2021, Warsaw ranked 6th among cities with the lowest air quality according to the Air Quality Index (Krzysztoszek & Jakubowska 2021). Additionally, the World Air Quality Ranking in February 2021 identified Warsaw as the city with the second-worst air quality globally, with PM_{10} concentrations exceeding by 232% and $PM_{2.5}$ levels by a staggering 364% (Kołodziej, 2021). Subsequently, in March, Warsaw topped the IQAir ranking as the most polluted major city in the world (IQAir, 2022), underscoring its selection as the research focus. The average daily lowest temperature was recorded at 8.2°C, and the average daily highest temperature reached 15.9°. The average daily lowest humidity rate was 71.9%, the recorded highest daily humidity rate was 90.1%. Wind speed during the analyzed period ranged from 2 to 7 m/s with gusts of 4 to 16 m/s occurring. Precipitation occurred 3 times - 2.4 mm of rain fell on September 23, 0.4 mm of rain on September 24 and 4 mm of rain on September 30. In summer, Warsaw is most often affected by winds from the west (24.7%) and north-west (10.7%), while in winter south-westerly winds prevail, and in spring and autumn gusts from the east and south-east dominate.There were no sudden changes in atmospheric conditions during the analyzed period.

The tree inventory was conducted along two 500-meter sections in Warsaw, Poland, chosen for their varied tree canopy cover and essential role in city communication (Table 2), experiencing heavy traffic throughout the day, with an average of 1070 cars per hour on Marszałkowska Street and 1049 cars per hour on Żwirki i Wigury Street during rush hour (Municipal Road Administration 2021). Traffic measurement points coincided with the tree inventory locations at spot 2307 on Marszałkowska Street and spot 1306 on Żwirki i Wigury Street (Municipal Road Administration 2021). Both streets feature similar geometry, minimizing variability in pollution level measurements, as they lack bends or curves. Traffic characteristics (heavy traffic lane) at both studied locations and the characteristics of the tree system - a linear alley system, and the way the measurements has been carried out - measurements recorded along the alley, have registered the linear characteristics of air purification in the studied alley sections. Both of these streets, as shown by the orthophoto (Figure 1) are not canyons according to the accepted definition ($H / W \geq 1$) (Wan Mahiyuddin et al., 2013). None of the industrial emitters of pollution were located near the surveyed street sections (Spatial Information System 2022). The trees along these streets grow in public areas and are easily accessible. Marszałkowska Street predominantly features concrete squares, wide pavements, and commercial buildings, with minimal surrounding shrubbery (Figure 2).

The street accommodates three traffic lanes in each direction, with a tree alley mostly comprising small-leaved linden trees (*Tilia cordata* Mill) planted in designated spaces between the pavement and the road. The surveyed section boasts a 6% tree canopy cover, with 59 trees averaging 18.05 cm in diameter and 5 meters in height. In contrast, Żwirki i Wigury Street (Figure 3), a primary thoroughfare bordered by four rows of trees, benefits from closer proximity to allotment gardens, resulting in a greater abundance of trees and other vegetation.

With two traffic lanes in each direction separated by small-leaved linden trees, the surveyed section hosts 142 trees averaging 11 meters in height and boasting a 31% tree canopy cover. Tree canopy cover was determined using QGIS.

2.2 Methodology

The principal sources of data utilized in the research included monitoring the $PM_{2.5}$ concentration levels in urban streets with differing tree canopy cover (TCC) densities (Karaczun & Michalak 2019) during peak traffic periods and post-peak traffic periods. Additionally, tree inventory was conducted in selected locations, and the i-Tree Eco tool was employed to calculate the pollution removal capacity. Through data collected from these sources, the authors aim to assess the impact of trees on air quality in two distinct locations, identify statistically significant differences, and analyze the measurement findings of actual pollution levels alongside estimates provided by the i-Tree Eco model.

2.3 Air quality monitoring

Air quality monitoring was conducted at two locations: Marszałkowska Street and Żwirki i Wigury Street. Air quality sensors were strategically placed in central areas of one alley covered by trees and another devoid of tree cover, positioned 3 meters away from the edge of the road. Temtop M2000 sensors (2nd Generation Multi Functional Air Quality Detector with TFT color screen—EN 60825–1W/A11 US 21 CFR 1040.10), versatile air quality meters capable of measuring $PM_{2.5}$, PM_{10}, CO_2, HCHO, temperature, and humidity, were utilized for this purpose. $PM_{2.5}$ concentrations were monitored at a height of 1 m above ground level, which is considered the breathing zone. Equipped with PM laser sensors and Non-Dispersive Infrared (NDIR) CO_2 sensor, the Temtop M2000 meter offers measurements with an accuracy of 0.1 µg/m^3 for $PM_{2.5}$ dust, within a measurement range of 0-999 µg/m^3 with a measurement range of 0.1–10,000 µg/m^3, a resolution and sensitivity of 1 µg/m^3, an airflow rate of 1 L/min, and calibrated with Arizona Road Dust as reference material (Temtop M2000 User Manual, 2022). After being switched on, the detector was calibrated for approximately 10 minutes and then placed outdoors for another 10 minutes to ventilate. Each individual measurement lasted one minute, during which the average $PM_{2.5}$ concentration was calculated and displayed. At each location, monitoring was conducted for at least 10 minutes, with data recorded every minutes, to ensure an accurate average value. If necessary, the monitoring duration was extended until the readings stabilized. To minimize the impact of changing environmental conditions, total monitoring time per location (street) was limited to 2 hours. Furthermore, the monitoring protocol required measurements to be taken in quick succession while in motion. Air pollution concentration levels were recorded every minute during the monitoring period, spanning from 24th September 2021 to 8th October 2021, across two distinct time intervals: during rush hour and post-rush hour. The study was carried out in September and October to coincide with the peak usage period of the road zone, which is primarily active during rush hours. This timing ensured that the assessment captured conditions most relevant to users, as well as the ecological and health impacts of these urban green spaces during their most active phase. Measurements were conducted in September–October, when trees typically retain full foliage, enabling reliable assessment of $PM_{2.5}$ removal efficiency. This timing also facilitates detecting vitality differences between zones with contrasting TCC, as high canopy cover helps sustain physiological activity, whereas low-TCC areas may show early stress symptoms reducing purification performance.

Each sensor was stationed at the testing sites for 60 minutes during each period. Rush hour was defined as the timeframe between 4:00 p.m. and 6:00 p.m. on Mondays through Fridays, while non-rush hour periods encompassed the remaining time, excluding the hours between 8:00 a.m. and 10:00 a.m. . The average daily temperature during the mentioned period ranged from 7.5 to 14.2°C, and maximum temperatures ranged from 13.3 to 20.3°C.

2.4 The i-Tree Eco model

The i-Tree Eco version 6.0 model guided the collection of field data following its prescribed protocols, as outlined in the i-Tree Eco User Manual (i-Tree Eco User's Manual, 2019). Following the software's recommendations, one of the two tree sample selection options was employed, entailing a comprehensive survey of trees within the designated area. A thorough examination of trees in the research area was conducted, with data collection performed as per established procedures (Kais et al., 2021). This encompassed documenting tree species and locations, alongside dendrometric measurements including trunk diameter (DBH), total tree height, live tree height, crown base, North-South crown width, East-West crown width, crown loss percentage, crown health, and crown light exposure. DBH measurements were obtained using a caliper at 130 cm above ground level, while measurements for other parameters were acquired utilizing a Bosch GLM120c laser measure with up to 0.5 m accuracy. Additionally, weather details and air quality data sourced from the i-Tree database, including $PM_{2.5}$ concentration levels measured by PM level monitors positioned in Warsaw, were incorporated into the model. The i-Tree database facilitated access to meteorological data and air quality information. Subsequently, upon inputting all requisite data, the model was activated to generate estimates regarding the pollution removal efficacy of trees along Marszałkowska Street and Żwirki i Wigury Street. Furthermore, to ascertain the statistical significance of air quality measurement disparities between tree-covered and low tree cover segments, an analysis of $PM_{2.5}$ concentration level differences was conducted utilizing R software. Canopy cover measurements were taken using GIS software and correlated with field measurements. Dendrometric measurements and tree species identification were performed by a qualified landscape architect. The average parameters are shown in Table 1.

Table 1. Average tree growth parameters

Measured parameter	Street name	Value (with Standard Error)
DBH [cm]	Marszałkowska	18,05±11,43
	Żwirki i Wigury	38,82±9.72
Total Tree Height [m]	Marszałkowska	5,18±2,40
	Żwirki i Wigury	11,17±2,34
Crown Width NS [m]	Marszałkowska	3,42±2,05
	Żwirki i Wigury	7,71±2,10
Crown Width EW [m]	Marszałkowska	3,18±2,16
	Żwirki i Wigury	7,78±2,21
Crown Miss [%]	Marszałkowska	18,22±22,75
	Żwirki i Wigury	12,89±15,97

Tree health assessment was performed by determining the percentage of crown loss, in accordance with the i-Tree Eco methodology (i-Tree Eco User's Manual). Crown loss was expressed as an estimate of the percentage of dead branches in the crown of each of the trees studied during field inspections.

2.5 Statistics

To illustrate the $PM_{2.5}$ air pollution levels on Żwirki i Wigury Street and Marszałkowska Street, a comparison of average air pollution and the duration of recorded pollution levels (in minutes) in two categories: below 15 μg/m^3 and above 15 μg/m^3 was conducted. Both sets of data were presented by date and measurement time (high traffic or after the peak traffic). The results were analyzed using the pivot table tool in Microsoft Excel spreadsheet software. Additionally, line graphs were generated to depict the pollution levels on both streets throughout the entire study period.

3. Results

3.1. Air quality measurement

The research yielded data on pollution concentration levels in two locations: Marszałkowska Street and Żwirki i Wigury Street (Tables 2 and 3). Pollution level measurements were conducted over 9 consecutive days, totaling 1074 minutes at a road segment with low tree density (Marszałkowska Street) and 1189 minutes in a tree-lined alley at Żwirki i Wigury Street. An overview of concentration levels in both locations is provided in histograms (Figures 2 and 3), while the average pollution levels at each street are shown in the tables.

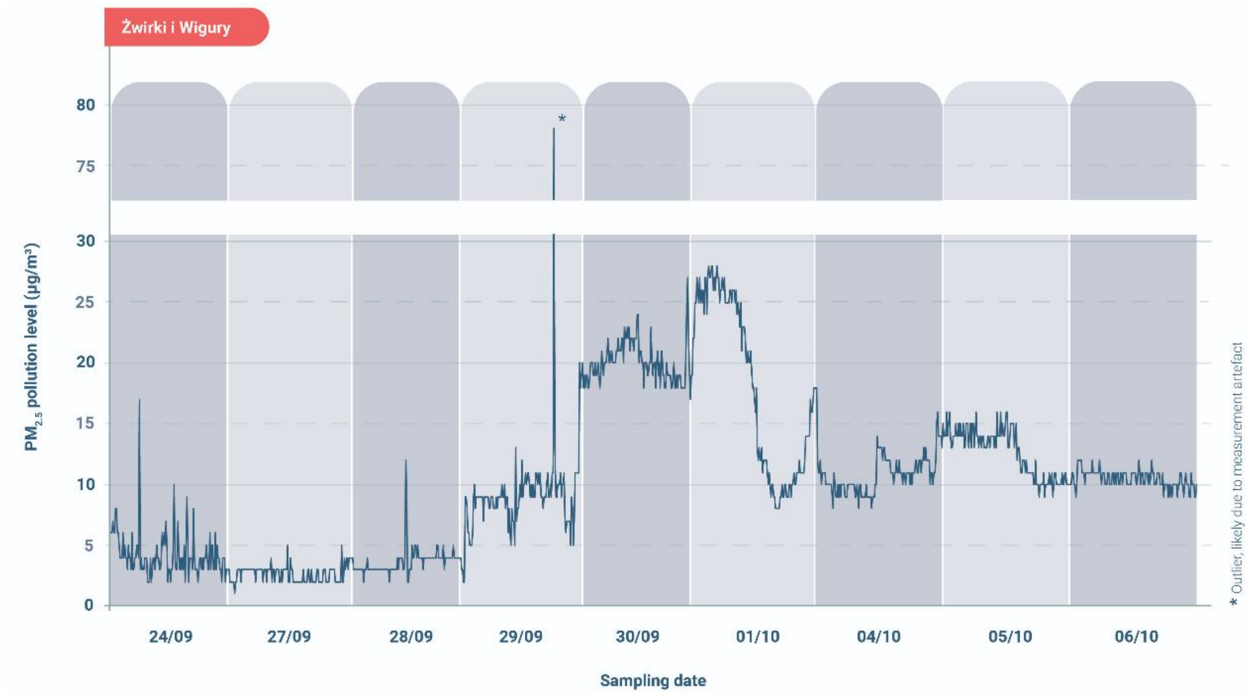

Figure 2. Żwirki i Wigury Street – $PM_{2.5}$ pollution level.

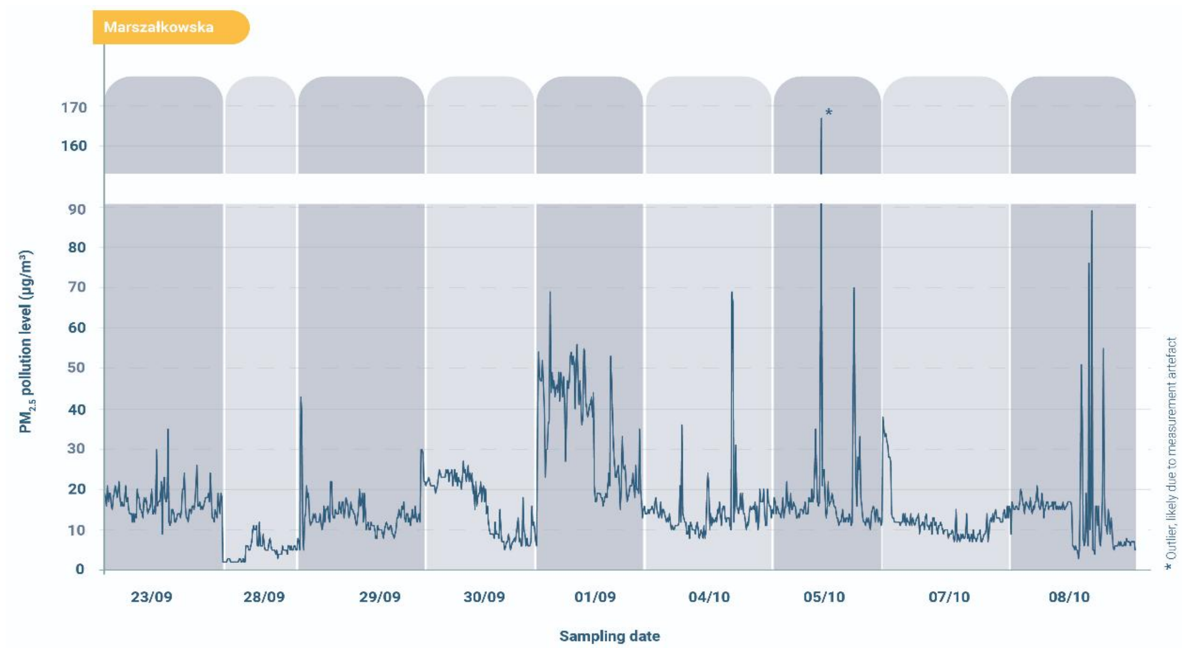

Figure 3. Marszałkowska Street – $PM_{2.5}$ pollution level .

Monitoring was simultaneous in both locations, and any discrepancies may result from occasional failure to register current pollution concentration readings. Tables 2 and 3 depict exceedances of $PM_{2.5}$ levels by peak hour, post-peak time, and total exceedance time by street. $PM_{2.5}$ limits exceeded by values higher than 15 µg/m^3 were recorded 1.5 times more frequently on the street with low tree cover. Furthermore,

$PM_{2.5}$ limits exceeded by values higher than 15 µg/m^3 occurred 3.5 times more frequently in the same area, and limits exceeded by values higher than 25 µg/m^3 happened 14 times more frequently. Dust concentrations are also illustrated in the graphs (Figs. 2 and 3). Considering a similar level of traffic congestion and the same tree species in both locations, it can be inferred that the main reason for the difference in pollution concentration levels is the poorer condition of trees at Marszałkowska Street. The trees there grow in designated spaces cut out in the pavement (1,9x1,9m), resulting in inadequate access to water and insufficient space for root system growth. As a consequence of these harsh site conditions (high concentration of paved areas), tree canopy cover is only 6% in that area.

Statistical analysis was conducted based on the collected data on PM concentration levels. A Shapiro-Wilk distribution test, covering $PM_{2.5}$ concentration levels at roads with low and high tree canopy cover, revealed significantly different distribution patterns from the norm ($p < 0.05$). Additionally, a parametric Mann-Whitney test was performed to assess the sum of ranks. The resulting sum provided the rank difference, aiding in categorizing groups into two separate populations. This test showed a significant difference ($W = 341450$, $p < 0.05$) between concentration levels in a street covered with trees and a street with low tree cover. The median for $PM_{2.5}$ concentration levels was 14 µg/m^3 in the segment of the street with low tree canopy cover and 10 µg/m^3 in the tree-covered alley. Additionally, an ANOVA table test was performed. The ANOVA table tests the overall significance of the model. The F-statistic of 120.103 with a p-value less than 0.001 indicates that the model is statistically significant, meaning at least one of the predictors has a significant impact on $PM_{2.5}$ removal value levels (Table 4). The multiple linear regression model demonstrates a strong relationship between the predictors (Crown % Miss, Total Tree Height, and Diameter) and the dependent variable ($PM_{2.5}$ removal value. The R-value of 0.837 suggests a high correlation between the predictors and the dependent variable. The model explains 70.1% of the variance in $PM_{2.5}$ removal value, as indicated by the R^2 value of 0.701. The adjusted R^2 is 0.695, meaning that the model maintains its explanatory power even when adjusting for the number of predictors. The table of coefficients provides insights into the individual contributions of each predictor: Diameter: The coefficient is 0.244 ($p < 0.001$), indicating a positive relationship between tree diameter and $PM_{2.5}$ removal value. A one-unit increase in Diameter is associated with a 0.244 increase in $PM_{2.5}$ removal value, holding other variables constant. Total Tree Height: The coefficient is 1.142 ($p < 0.001$), showing a strong positive impact on $PM_{2.5}$ removal value. An increase in tree height by one unit results in a 1.142 increase in $PM_{2.5}$ removal value. Crown % Miss: The coefficient is -0.148 ($p < 0.001$), meaning that a higher percentage of missing crown coverage reduces $PM_{2.5}$ removal value. For every 1% increase in Crown % Miss, $PM_{2.5}$ removal value decreases by 0.148. All predictors are statistically significant at the 0.001 level, confirming their strong contribution to the model.

3.1 The i-Tree Eco model

To prepare the model using the i-Tree Eco tool, a tree inventory was conducted at Marszałkowska Street (a segment with low TCC) and at Żwirki i Wigury Street (a segment with high TCC). The analysis of the tree inventory revealed that there were 59 trees along Marszałkowska Street, with the dominant species being *Tilia cordata* Mill. The diameter of the trees at Marszałkowska Street ranged mainly between 7.6 cm and 15.2 cm. Along the tree alley at Żwirki i Wigury Street, there were 142 trees, also predominantly *Tilia cordata* Mill., with diameters mainly between 30.5 cm and 45.7 cm (Table 1).

According to the i-Tree Eco report, the research was conducted on 500-meter-long street segments. After inputting the data, a model was launched using current data in the i-Tree Eco database on air pollution and meteorological conditions. The i-Tree Eco model assessed that the tree stand at Marszałkowska was capable of removing approximately 105.7 g of $PM_{2.5}$ over the course of a year, while the tree stands at Żwirki i Wigury had the capacity to remove 1.52 kg of $PM_{2.5}$ in a year. The highest value of $PM_{2.5}$ absorption for a single tree at Żwirki i Wigury was 24 g over the whole year, while the result for Marszałkowska was 19.9 g. Tables 2 and 3 show average values of $PM_{2.5}$ absorption for a single tree over the course of a year, indicating the variability of dust absorption throughout the year and in specific months in both locations.

Table 2. Measurement of pollution levels at Marszałkowska Street.

	Time of recorded pollution levels lower than 15 μg/m³ [in minutes]			Time of recorded pollution levels higher than 15 μg/m³ [in minutes]		
Date	After the peak traffic	High traffic	Total	After the peak traffic	High traffic	Total
24.09.2021	14	22	36	40	32	72
27.09.2021	35	83	118	17	2	19
28.09.2021	0	52	52	60	5	65
29.09.2021	0	49	49	60	10	70
30.09.2021	48	5	53	8	50	58
01.10.2021	16	32	48	34	20	54
04.10.2021	63	33	96	9	20	29
05.10.2021	3	56	59	43	2	45
06.10.2021	3	52	55	44	12	66
Average (with Standard Deviation)	20,22±23,15	42,67±22,56	62,89±26,37	35,00±19,84	17,00±15,81	53,11±18,66

Table 3. Measurement of pollution levels at ul. Żwirki i Wigury.

Date	Time of recorded pollution levels lower than 15 µg/m³ [in minutes]			Time of recorded pollution levels higher than 15 µg/m³ [in minutes]		
	After the peak traffic	High traffic	Total	After the peak traffic	High traffic	Total
24.09.2021	66	64	126	2	0	2
27.09.2021	63	61	124	0	0	0
28.09.2021	66	65	131	0	0	0
29.09.2021	62	62	124	0	1	1
30.09.2021	0	0	0	65	63	128
01.10.2021	0	58	58	66	8	74
04.10.2021	65	65	130	0	0	0
05.10.2021	60	66	126	8	0	8
06.10.2021	66	65	131	0	0	0
Average (with Standard Deviation)	49,78±28,30	56,22±21,24	105,56±45,84	15,67±28,37	8,00±20,79	23,67±45,95

Table 4. ANOVA test results for the regression model predicting $PM_{2.5}$ concentrations using Crown % Miss, Total Tree Height, and Diameter as predictors.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3956,983	3	1318,994	120,103	<,001b
	Residual	1691,262	154	10,982		
	Total	5648,244	157			

a. Dependent Variable: $PM_{2.5}$

b. Predictors: (Constant), Crown %Miss, Total Tree Hight, Diameter

The average value of $PM_{2.5}$ absorption for a single tree at Marszałkowska was 0.009 g, while the result for Żwirki i Wigury was 0.12 g. The highest capabilities of $PM_{2.5}$ pollution absorption at Żwirki i Wigury were recorded in September and October, while records for Marszałkowska indicate the highest results in May, September, and October. The observed differences in the test results for average pollutant uptake by a single tree may be attributed to the smaller canopy cover of the trees at Marszałkowska and their limited growing conditions, as they were planted in small pits with restricted access to soil, which affected their health

4. Discussion

As awareness of the impact of pollution on human health and the environment grows, measures to reduce urban air pollution are gaining prominence. Among these measures, planting trees has been identified as one of the most effective ways to mitigate dust and other pollutants (Przybysz et al., 2018). Encouraging activities aimed at expanding wooded areas is therefore reasonable. Previous research conducted in Warsaw demonstrated that trees have the capacity to absorb significant amounts of air pollutants annually (Kais et al., 2021). The study found that one tree on Marszakowska Street absorbs an average of 89.38 grams of pollution per year, while a tree located on Zwirki i Wigury Street absorbs 390.39 grams of pollution per year. The result for individual trees was on average 4.5 times higher at Żwirki i Wigury Street. Our research confirms the finding that tree planting is an effective means of absorbing particulate matter. According to i-Tree Eco model estimates, an avenue with large, mature trees absorbs 1.52 kg of $PM_{2.5}$ per year, while an avenue with small trees planted in tree pits set in the sidewalk absorbs only 105.7 g of $PM_{2.5}$ per year.

Annual PM exposure map prepared by Fisher et. al.,(2005) shoved that around 10 % of the central city were those with pollutants concentration above the 20 μg/m^3 i.e. exceeding national annual guidelines. In our study, we found that even areas placed close to each other but differing by TCC could have different pollutant absorption-$PM_{2.5}$ limits exceeded by values higher than 15 μg/m^3 were recorded 1.5 times more frequently on the street with low tree cover. Furthermore, $PM_{2.5}$ limits exceeded by values higher than 15 μg/m^3 occurred 3.5 times more frequently in the same area, and limits exceeded by values higher than 25 μg/m^3 happened 14 times more frequently, which indicates the importance of detailed empirical analyses to complement the results obtained with the i-Tree model, essential in the decison-making process concerning urban forest planting and maintaining polices. In New Zealand, over a year trees have been removed approx. 300 tons of air pollutants in the area of Christchurch (Cavanagh , 2008) but according to our results the same size of the studied area could have significantly different air pollution removal potential. It was found in the UK that planting trees on a quarter of the available urban area may lead to a decrease in PM_{10} concentration by 2 to 10% (McDonald et al., 2007) in our study potential of mature and in good vitality trees was more than 14 times higher in comparison to trees growing in poor site condition in the empirical study. Considering similar levels of traffic volume and the same tree species in both locations, the median for $PM_{2.5}$ concentration levels was 14 μg/m^3 in the segment of the street with low tree canopy cover and 10 μg/m^3 in the tree-covered alley. Our results highlight the potential of high-quality green infrastructure to improve the well-being of urban residents, particularly those exposed to elevated concentrations of $PM_{2.5}$. The accepted daily standard for PM2.5 is 25 μg/m^3. In this study, we monitored actual PM2.5 concentrations, and the findings revealed notable spatial differences. Marszałkowska Street recorded 28 exceedances above the permissible threshold during peak hours, whereas Żwirki i Wigury Street recorded only 2 exceedance. As research specifies, particulate matter (PM) has the most detrimental effect on public health and the environment (Fisher et al., 2005; Russell & Brunekreef, 2009). It is due to the size of the particles - hence anthropogenic dust is considered the highest risk to human health (CAFE, 2004). Inhaling PM causes the particles to accumulate in lung tissue and enter the bloodstream, which in turn leads to a higher risk of circulatory and pulmonary illnesses (Cen, 2015), obstructive pulmonary disease, and lung cancer (Jeong, 2013). Research shows that lung cancer incidence in Beijing was 1.055 for men and 1.149 for women and the increase in incidence was caused by the increase of $PM_{2.5}$ levels by 10 mg -3 (Guo et al., 2014). Inhaling dust also causes deterioration of health in respiratory illnesses such as asthma (Bond et al., 2013; Brauer et al., 2007) and leads to respiratory infections in children (Bond et al., 2013). The i-Tree data shows that the absorption of pollutants in the low-density tree canopy cower area is 14 times lower but does not show how often pollution exceeds levels dangerous to the health of city dwellers, so the novelty of our study is to provide new information illustrating the risks to human health and life and to determine periods of time when the health risk is significant. This knowledge allows countermeasures to be taken, ranging from alerting residents to taking action to improve the quality of green infrastructure, for example through efforts to increase tree canopy cover and as a result risk mitigating. Studies using models like the i-Tree Eco model in Barcelona and the UFORE model in Perth have quantified the removal of air pollutants by urban forests. The survey was conducted for the entire city area, where tree canopy coverage is 22%. In the case of the study from Australia, the amount of PM_{10} removed was converted to m2 and was 16.0 g/year/m^2. However, there is a need for tools that are validated with actual pollution data, as many studies rely on models. The i-Tree Eco model, while widely available, lacks studies verifying its accuracy, especially regarding comparisons of dust concentrations in areas with varying vegetation cover. Our study aimed to address this gap by comparing actual pollution measurements with i-Tree Eco model estimates in areas with different tree canopy cover. Although the results of analyses using the model for cities have been conducted (Szkop, 2020) but there is a lack of verification using empirical methods that provide data on the specifics of pollution distribution. From the results of our study, it can be concluded that urban trees contribute to improving urban air quality and human health. However, there are uncertainties regarding the accuracy of tools like the i-Tree Eco model in estimating pollutant absorption. Further research is needed to validate and refine these models.

Studies conducted in various locations, including Warsaw, Shanghai, New Zealand, and China, have shown that trees are effective in reducing air pollution levels. However, the effectiveness of trees in absorbing pollutants may vary depending on habitat conditions and tree canopy cover. Our study highlights the importance of adequate tree canopy cover in urban areas for maximizing the benefits of air pollutant removal crucial for the prevention of human health toxicity from exceeding air pollution norms. The analysis of air quality standards in Warsaw indicates that exceedances of these standards are frequent, particularly during peak hours. This underscores the need for further research on urban trees and air pollution using dust sensors, as most studies to date have relied on models rather than experimental data (Szkop, 2020; Kais et al., 2021). Holnicki et. al. (2017) conducted a study that consisted of running a model in the CALMET/CALPUFF tool. Based on the model, they determined the most polluted places in Warsaw. Work with the execution of generalized regression models (GRM) was also carried out by Majewski et. al. (2014). The impact of air pollution on visibility in the Warsaw metropolitan area, which was determined based on the aforementioned model, was investigated.

Despite the conclusions of King et. al. (2014) that who suggested that tree canopy cover likely has at most a small impact on neighborhood air quality visible in $PM_{2.5}$ concentration and represents a lack of pollution sources rather than active pollution removal we have found that on the same type of urban site and location in the city center, but with low tree canopy cover – 6% TCC (Marszałkowska Street), $PM_{2.5}$ absorption was found to be almost 14.5 times lower than on area with tree canopy cover meeting the assumptions of optimal green infrastructure density – 31% (Żwirki and Wigury Street). We assumed rather than the habitat conditions of the trees at Żwirki i Wigury Street positively affect the possibility of greater absorption of pollutants through greater opportunities for tree growth. According to Urban (2008) and Trowbridge et. al. (2004), trees need a suitable rooting space to develop properly and at the same time maximize ecosystem services. In the case of studied trees (average DBH is 18,05 cm) recommended soil volume for rooting is 13 m^3 (Trowbridge et al., 2004) in reality, tree pits provide 3,6 m^3 for rooting. Difficult habitat conditions (isolated tree pits) on Marszałkowska Street resulting in poor tree health, limit the ability of trees to absorb air pollutants. Maximizing ecosystem services in this area requires modifying (improving) habitat conditions. A study by Warsaw scientists (Olchonwik et al., 2023) showed that trees with limited rooting areas have more difficult conditions to develop than trees growing in the reserve. The differences associated with the number of mycorrhizal tops and mycorrhizal species were related to organic matter levels and soil chemical parameters, which were less favorable for root development in the rooting space limited by paving. Moreover, 25 years long research was conducted on the average life span of trees in roadside greenery zones (Dmuchowski & Badurek 2001), which showed that the average life expectancy of trees growing in small tree pits along Marszałkowska Street was 10-12 years. This indicates that it is not possible for a tree to reach full maturity and therefore high ecosystem service provision in excessively limited rooting space, common in urban locations.

5. Conclusion

Different levels of dust concentration were recorded on both streets depending on tree canopy cover. On the street with 6% tree canopy cover and poor habitat conditions (tree pits), exceedances of the WHO air quality standards (15 $\mu g/m^3$) were recorded 1.5 times more frequently. The results indicate that the effectiveness of purification depends on tree canopy cover. The compared avenues differ in terms of the occurrence of

PM pollutants hazardous to health according to WHO standards (15 μg/m^3) – on Marszałkowska Street, this type of pollution was recorded 1.5 times more often than on Żwirki i Wigury Street. All trees on Marszałkowska Street grow in pots with a maximum size of 1.9 x 1.9 m. Tree canopy cover is 25 pp. greater on streets with good site conditions for trees (separate green belt). On this basis, it can be inferred that under favorable site conditions, an increase in TCC is positively correlated with enhanced $PM_{2.5}$ capture capacity. The use of the potential of urban areas, expressed in the availability of optimal site conditions for the healthy growth of trees resulted, in our study, in more than 14 times greater effectiveness of trees in cleaning the air from $PM_{2.5}$. Our study contributes to this effort by providing empirical data on the effectiveness of trees in mitigating air pollution, but more research in context of site condition and potentially correlated TCC is warranted to fully understand the complexities of this issue. In conclusion, while there is growing public awareness of the importance of addressing urban air pollution, further research is needed to inform evidence-based decision-making in this area.

The limitations of our work are the period during which the data was collected; the work does not cover the entire year. Furthermore, comparison with municipal data was impossible due to excessive variability on small sections of streets and the distance of municipal sensors from the selected research site. It would also be advisable to install dedicated sensors that would enable comparison with municipal data

Author contributions

Conceptualization: Karolina Kais, Marzena Suchocka; methodology: Karolina Kais, Marzena Suchocka, ; writing—original draft preparation: Karolina Kais, Marzena Suchocka, Marlena Gołaś, Maciej Ziemiański, Hazem M. Kalaji; writing—review and editing, Karolina Kais, Marzena Suchocka, Marlena Gołaś, Maciej Ziemiański, Hazem M. Kalaji. All authors have read and agreed to the published version of the manuscript.

Ethical Approval

Not applicable

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Conflicts of interest

The authors declare no conflict of interest.

Availability of data and materials

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